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COMPASS DIAL BEARING
INDICATOR FOR ACOUSTIC SIGNALS
S. N. Heaps

Technical Report No. 680(00)-6
February 22, 1954

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The research reported in this document was done under ONR Contract No. 680(00) between the Office of Naval Research and the Magnolia Petroleum Company.

Magnolia Petroleum Company
Field Research Laboratories
Dallas, Texas

Report by

S. N. Heaps

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COMPASS DIAL BEARING INDICATOR FOR ACOUSTIC SIGNALS

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COMPASS DIAL BEARING INDICATOR FOR ACOUSTIC SIGNALS

I. INTRODUCTION

Early in the development of an acoustic intensity meter, under Contract Nonr-680(00), multiplication of signals from pressure and velocity detectors was performed by standard dynamometer type instruments. With the advent of a suitable electronic multiplication circuit, the work was divided into two phases: (1) development of an all electronic multiplication and display system, and (2) development of an electrodynamometer type system. Interest in the second system continued only because it was realized that the two dynamometers which were formerly used could be combined into one unit with a single pointer. This simple device could be expected to perform not only the operations of multiplication and integration formerly performed by the two instruments, but it would also effectively indicate the direction of the vector sum of these products thus giving a direct indication of the direction of flow of acoustic energy. Complex equipment is required for doing this in the electronic system.

Certain commercially available instruments ordinarily used as power factor meters, phase angle meters, or synchroscopes already embody this combination of two dynamometers in one unit. Some of these were studied and an effort was made to utilize the elements of the most promising to construct similar instruments more closely meeting specific design requirements of the intensity meter. A preliminary evaluation of the best instrument we built is presented here together with comparative data on the commercial instruments.

It is concluded that the device described could be used as part of a sonic bearing system. It is recommended that a more refined model of the instrument be designed by qualified instrument makers and that further operational tests of the whole system be initiated.

II. ACOUSTIC BEARING INDICATION BY INTENSITY MEASUREMENT

Acoustic intensity is a vector quantity with a sense that indicates the direction of energy flow. Apparatus responding to true intensity must therefore have as an inherent operational feature the means for sound direction computation or display. Underwater sound waves consist of pressure variations and vibratory motion of the water. Both pressure and vibration velocity have the same wave form. The product of these two quantities at any moment may be considered as an instantaneous value of the sound intensity with its sense corresponding with that of the velocity. Since the sound waves are longitudinal vibrations, this velocity amplitude direction is the same as the direction of the progression of the sound wave fronts themselves. Intensity also may be considered as a flow of energy-as ergs per second per square centimeter. This flow may be averaged over a period of time to give a net direction of flow even in the presence of numerous sound sources of random position. In this report an indication of the direction of wave progression or energy flow is called an acoustic bearing. Since no net flow of energy results from the random sound sources, good bearing indication may be expected under poor conditions of signal-to-noise amplitude ratio.

III. ELECTRODYNAMOMETER

The term electrodynamometer best describes our instrument since it operates on a torque balance principle. The operation of the iron vane instrument will be presented in detail in the description of the specific model which was designed, constructed, and tested. Different forms of the electrodynamometer are used in phase angle or power factor meters and in synchroscopes, and its use as a watt meter is well known.

The dynamometer can perform the function of addition. This may be done by letting two or more torques act independently upon the same shaft in the instrument. Its response is the result of the sum of all torques acting on it. Addition may also be done magnetically. If one torque on the shaft is proportional to a magnetic field strength in the instrument, this field may be the sum or resultant of superposition of several discrete fields of independent origin. Both types of addition are used in the acoustic bearing indicator.

Time integration or averaging may be performed in the dynamometer by viscous damping of the shaft motion. If the damping is large, the angular velocity of the shaft is always proportional to the torque. The velocity times the time gives the displacement. The angular displacement or position of the shaft is thus a time average of the torque. This property is used in the device to decrease the shaft's response to the vibratory components in the applied torques.

Multiplication is obtained in the dynamometer through the interaction of field coils and rotor coils and their associated magnetic fields. The

torque on the shaft is proportional to the current in the field coil and to the current in the rotor coil. The shaft response is therefore proportional to the product of the two currents. This function of the instrument is utilized in watt meters. Here the torque due to coil currents is balanced by that of a hair spring with the shaft position being indicated on an appropriate scale. In this case the coil currents are made proportional to a voltage and to the associated current in the external electric circuit being measured. The coil currents in the acoustic bearing indicator are made proportional to velocity and pressure signals in the underwater sound field. The torque on the shaft is then proportional to the instantaneous value of the intensity of the sound. If this torque were to be balanced by a hair spring at some shaft position, an indication of one component of sound intensity amplitude would result. However, no such springs are present since torque balance is provided by the other intensity component.

The moving coil dynamometer presents a difficult problem in making electrical contact with the movable parts without appreciable friction. Flexible spring connections minimize the problem, but do not permit a design having a 360 degree dial. This objection can be overcome by the use of switching circuits, although no effort has been made in this direction.

The attractiveness of the iron vane design lies in its freedom from electrical connections to the moving parts. Its efficiency is increased by the high permeability of the iron in the vane. The induced polarity in the iron vane by the field coils, however, reduces the maximum efficiency that might be realized.

A more complete description of the entire acoustic bearing system is available in earlier reports of this project. Figure 1 is a block outline of the whole system using the iron vane type indicator. Three sound detector are shown suitably mounted at the same place under water. The pressure signal detector is non-directional. The two velocity detectors have mutually per- pendicular orientation of their lobes of maximum sensitivity. A compensator in the pressure signal channel gives this channel the same amplitude and phase characteristics as the velocity channel. The signals are amplified and fed to the iron vane type instrument. This device multiplies the appropriate signals, integrates the products over a period of time, adds the two vector components of intensity thus formed, and displays the result as a bearing indication.

IV. MODEL M-IV INSTRUMENT

A. General Description

A sectional perspective view of the main elements of the instrument is shown in Figure 2. It has been designated as the Model M-IV. The compass dial is about 3.5 inches in diameter. The vane arms are about 0.75 inch long and 1.6 inch apart on the vertical shaft. The shaft is free to turn in jewel bearings. It also carries a damping fin in the oil at the lower end of the shaft, and the indicating pointer near the top end of the shaft. The shaft passes through the center of the vane coil which is located between the upper and lower vane arms. Currents in this coil produce corresponding magnetic poles on the outer ends of the two vane arms. As they rotate, the vane arms always lie in the magnetic fields produced by the upper and lower field coils. The whole assembly is mounted in a metal box with the dial and top jewel visible from above. The M-IV dynamometer unit weighs about one pound.

The operation of the instrument may be described in terms of its magnetic fields. The field coils at the upper and lower vane arms are identical. Upper and lower coils with the same orientation are connected in series to form one velocity signal circuit but producing two equivalent fields at the upper and lower vane arms. The other velocity circuit is similar except that the associated magnetic fields are perpendicular to those of the first velocity coils. The resultant field at each vane arm depends on the instantaneous polarity and relative amplitudes of the two velocity signal currents. Two horizontally sensitive velocity detectors in the underwater sound field with mutually perpendicular orientation of sensitivity axes

provide the signals for these coils. The magnitude of each velocity component of the sound field gives rise to a corresponding component of magnetic field strength in the instrument. The resultant fields of both vanes is thus equivalent to the sound velocity with respect to magnitude and direction. A pressure sensitive detector located in the sound field at the same point energizes the vane coil of the instrument to produce poles on the vane arms with the intensity of magnetization dependent upon the sound field pressure. The torques are proportional to the product of the pole strength of the vane and the field strength produced by the field coils, and, therefore, are proportional to the product of the pressure and velocity amplitudes of the sound field. The vane turns like a compass needle to a position of zero torque. This is the position where the vane arms line up with the magentic field due to the velocity signal coils. Hence the pointer stops in a position representing the direction of travel of the sound wave producing the signals.

The torque on the vane is proportional to the instantaneous product of the sound pressure and velocity and would therefore be pulsating. The vane's inertia prevents it from responding to these pulsations, and its motion depends more on an average value of the product. The torque producing the motion is thus proportional to the sound intensity. Further damping is obtained by the fin in the oil dash pot to increase the averaging time.

The system is insensitive to noise from numerous sources of random positions by virtue of three effects. They may produce out of phase current relationships between vane and field coils which produce no net torque on the vane. They may produce out of phase current relationships between the crossed field coils to cause rotating components of magnetism in the field which are

too rapid for the vane to follow. Finally, they have no net flow of energy over any great length of time. The final position of the indicating needle is the result of integration of all torques over a time of a few seconds. The torques due to such random noise are small whether the noise is acoustic or electrical. Good operation under conditions of poor signal-to-noise ratio is therefore to be expected.

B. The Dynamic Range of Power

The maximum and minimum power requirements are related to the acoustic signals and noise. In the presence of a poor signal-to-noise ratio the indicating needle shows small but continuous erratic motion. The amount of erratic motion may be decreased by using heavier oil or otherwise increasing the damping of the vane motion. The noise signal currents present in the coil cause heating but produce no bearing indication. The simultaneous weak sound signal currents present must produce sufficient torque to operate the device. The dynamic range of power for the instrument has been defined to express an evaluation of the degree to which noise and signal can be present simultaneously and still have satisfactory operation. It is defined as the ratio of power for normal heating to the power for a small movement of the vane. Since no torque is produced when the vane arms are in alignment with the field, a 45 degree position is selected when minimum power measurements are made. A series connection of a velocity coil and a vane coil is used to insure equal current in both coils. The minimum power is not difficult to observe because a pointer movement of several degrees occurs at the moment the applied power is sufficient to overcome the static friction of the vane bearings. A range of 28 db has been obtained in the M-IV instrument. More

careful construction of the bearings would probably give another 20 db by reducing the lower power limit. The upper power limit could be increased by using materials that would have long life at higher temperatures or by making a larger instrument.

C. Static Friction

Static friction in the vane bearings sets the lower limit on the power necessary to operate the instrument. An increase in quality of the bearings should increase the range of usable signal level and for this reason methods of reducing bearing friction were studied and the friction of the Model M-IV was compared with commercially available instruments. A value of 1.64 dyne cm static friction torque was measured in the M-IV instrument. Preliminary models with less rugged jewel bearings were found to have 0.622 dyne cm. In a Simpson volt meter the value was found to be 0.007 dyne cm. This small value undoubtedly reflects the influence of the light weight armature used. Comparable friction had been expected in the Model M-IV, however, some modification is necessary before such a figure can be realized.

D. Efficiency

The dynamic range could be increased in a design which gives more vane torque for the same applied signal power. An operating efficiency index for the dynamometer has been established as the ratio of torque on the vane to power dissipated by the field coil. This is with the same current flowing in vane coil and field coil, and with the vane 45 degrees off the null position.

The index was set up in this way because comparison with a Simpson dynamometer type volt meter was desired, and with the armature coil and field coil in series, both instruments dissipate a little more power in the field.

A value of 487 dyne cm per watt for the Model M-IV compares favorably with a value of 180 for the commercial instrument.

E. Mechanical Constants and Integration Time

It is desirable that the pointer move quickly to an accurate and stable position with a minimum of overshoot. Its motion is a function of the vane rotational stiffness, inertia, and damping. The averaging time, or integrating time, and speed of response can be determined from evaluation of these same mechanical constants and from the related torques due to currents in the coils.

Suitable laboratory tests led to determination of the mechanical constants of interest. The rotational inertia of the iron vane is about 2 gm cm^2.

The rotational stiffness or stability of a bearing indication is:

$$1.71 \times 10^3 \text{ dyne cm per radian per amp}^2.$$

Here the amp^2 is the product of vane current and field current. The value is accurate for small displacements only as nonlinearity of stiffness is associated with large angles.

The fin in DC 200 oil gives a viscous damping torque of 22 dyne cm per rad. per second.

Several different time concepts are significant in describing the instrument operation. Response time is an indication of the speed with which a bearing indication is established. Large torques give a short response

time and large damping forces give a long response time.

Integration time is the period in which a given value of pressure velocity product has an effect on the value of the acoustic intensity. It is also called averaging time since a true integration is not performed by our instrument. Furthermore the instrument has no exact period within which all products have proportionate influence and beyond which all products have no influence on the pointer position. Complete development of the concept is beyond the scope of this report. A long integration time is presumed to be related in a simple way with a long response time. Random source noises will have near zero intensity with a long integration time whereas a discrete sound source will give a very large intensity with a long integration time. In other words, a long integration time allows more chance for sound energy impulses to cancel out. It also allows more time for flowing energy to accumulate. With a long integration time smooth operation is obtained under noisy conditions.

The instrument time constant is more nearly the equivalent of an RC product in an electric analogy. It is also presumed to be related in a simple way to the instrument response time and integration time and is easily evaluated by laboratory methods. The ratio of damping to rotational stiffness gives the time constant for the system for a given current in the field and vane coils. This instrument time constant in seconds is found by dividing 1.28×10^{-2} by the product of the currents in the coils.

Since this time is a function of the coil currents, it is not analogous to the time constants of usefulness in the analysis of electrical circuits. Also the torque has a nonlinear relationship with the angular

displacement of the vane so that the time constant of the system changes with pointer position. Values near four seconds are normal instrument time constants.

F. Frequency Response

The instrument is designed to respond equally well to underwater sound frequencies between 20 and 500 cycles per second. This represents the band pass of the associated electronic amplifiers and detectors. It is necessary to have all coils in the device present similar loading on the signal amplifiers to prevent their production of phase shift between the various signal currents. Phase shifts would cause improper torque relationships. The coils have appreciable reactance and series resistors are used, providing a 70 percent factor near 1 kc, to give equal torque over the desired band. Some tests were successful in improving the efficiency at the sacrifice of frequency band width by operating the coils with condensers in series as resonant circuits. If filtering is to be done, it can be accomplished at this point in the system with an increase in efficiency rather than with an insertion loss. The instrument actually has no lower frequency limit and DC was used in some laboratory tests. The 20 cycle limit is imposed by the transformer coupling.

V. OPERATIONAL TESTS

Following laboratory tests which simulated field conditions, this instrument was tested at Lake Travis near Austin, Texas in December, 1953. Electric plugs were provided so that the dynamometer type bearing indicator and the electronic multiplier and cathode ray tube display could be operated from the signal amplifiers simultaneously. A small boat with an outboard motor served as a sound source. Good bearing indications were obtained on both display systems with the target boat circling the detectors at a radius of several hundred yards. These tests demonstrated that the M-IV indicator operated as expected but they did not permit a complete evaluation of the instrument. The absence of noise on these tests indicates that greater range is possible.

VI. COMMERCIAL INSTRUMENTS

The Westinghouse power factor meter type UY 25 has two rotor coils and a field coil positioned in proper manner for the instrument to be used for acoustic bearing indication. This instrument does not have a 360 degree dial, however, this does not eliminate its possible use as several ways are available for keeping the pointer on scale. Development of this method was not initiated.

A more serious difficulty in this design lies in the hair springs. These springs provide electrical contact for the rotor coils and in normal operation they exert very little torque on the rotor. With weak signals, however, this torque is enough to cause errors in bearing indication.

The instrument was refitted with a field coil more nearly suited to our driving transformer. A dynamic range of 60 db was measured between maximum power for normal heating and minimum value required for overcoming static friction. The hair springs prevent the actual realization of this range.

The instrument was found to have:

A rotor coil inertia of 3.7 gm cm^2

Static friction torque - 0.9 dyne cm

Rotational stiffness - - 3.08×10^3 dyne cm per radian per amp^2.

The magnetic moment of the rotor coil is related to its rotational inertia in a simple way. It is presumed that the higher value of rotational stiffness in this device as compared with the M-IV Model is consistent with the larger inertia of the moving element. The efficiency index mentioned for the M-IV

Model is not considered a suitable index for the UY 25 instrument and no value has been determined.

Tests have not been made on another Westinghouse Model KI-25. This power factor meter has the 360 degree dial and an iron vane movement. Major modification would be required to replace the 3-phase coils in it to fill the needs for using it as a bearing indicator. It was not considered suitable for the application.

VII. COMMENTS

The chief objective has been maintained in that acoustic bearings may be made with small detectors located at one point in the water. The simplicity of the dynamometer type sound bearing indicator is one of its main attractions. This is largely offset in the Model M-IV by the need of power amplifiers and associated power supplies. A smaller instrument operating directly from the voltage amplifiers is deemed practical and desirable.

An inherent disadvantage of this type of indicator is that the needle is always pointing to some position. Another instrument is needed to indicate whether or not energy is flowing. Such an indicator was made from a dynamometer volt meter with the rotor and field coils separately energized by a pressure and a velocity signal. The scale reading is proportional to the magnitude of either component of the sound effecting the M-IV instrument. The reading is zero when noise but no signal is present.

There are two positions of the vane with balanced or null torques. The one at 180 degree from the true sound bearing should be unstable. In the M-IV instrument polarization of the vane by field coil currents results in stability at the wrong null position. This wrong position is still less stable than the right one. If first one velocity signal and then the other can be interrupted for a moment, the needle then seeks the true stable bearing indication. The danger of an ambiguous reading would be minimized in an instrument in which polarization of the vane by field coil currents was minimized.

The dynamometer type system will probably not give bearing indications under as poor a signal-to-noise condition as may be obtained with the all electronic type acoustic bearing indicator. Noise voltages cause a continual fluctuation of the pointer. The signal-to-noise ratio of voltages applied to the M-IV instrument determines the accuracy of bearing indication. It was pointed out that the averaging time is a function of the applied currents. Since large noise impulses are averaged over a shorter time, their influence is disproportionately large. With true integration of torques the large noise impulses would not be disproportionate. It is also true that when the pointer is in the correct position, the signals cause no torques while noise arriving from different bearings produce high amplitude impulses which move the vane.

VIII. RECOMMENDATIONS

The Model M-IV iron vane unit can be used with suitable sound detectors and amplifiers for finding the bearing of underwater sound sources. In its present form it is not much smaller than other equipment used for these purposes and has disadvantages in dynamic range and stability in the presence of noise. We feel that these disadvantages can be overcome with better design, especially in the design of the vane bearings, and that an instrument of more nearly optimum design might have desirable features of size and reliability that cannot be realized with electronic systems. Therefore, further development of the instrument is recommended. The further recommendation is made, however, that this work be carried on by people, such as instrument designers, who are already familiar with the problems of making extremely low friction bearings and small efficient coils for producing strong magnetic fields. Further efforts to exploit the whole system are also recommended. Since the intensity may be evaluated at a single point in the sound field, small detectors may be used for long wave lengths of underwater sound.

APPENDIX

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FIGURE 1
SOUND BEARING SYSTEM
BLOCK DIAGRAM

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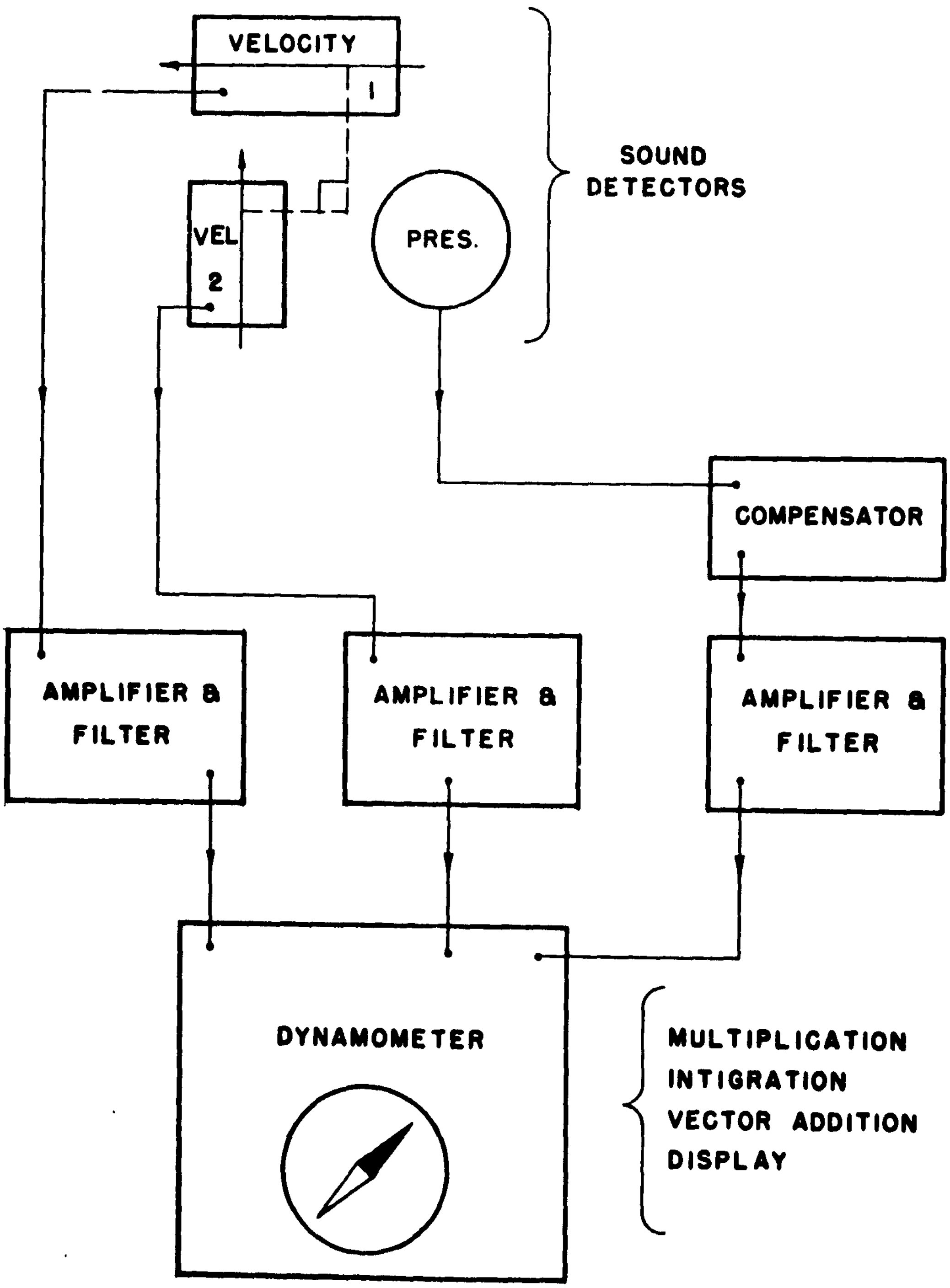

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FIGURE 2
MAGNOLIA PETROLEUM CO. IRON VANE DYNAMOMETER

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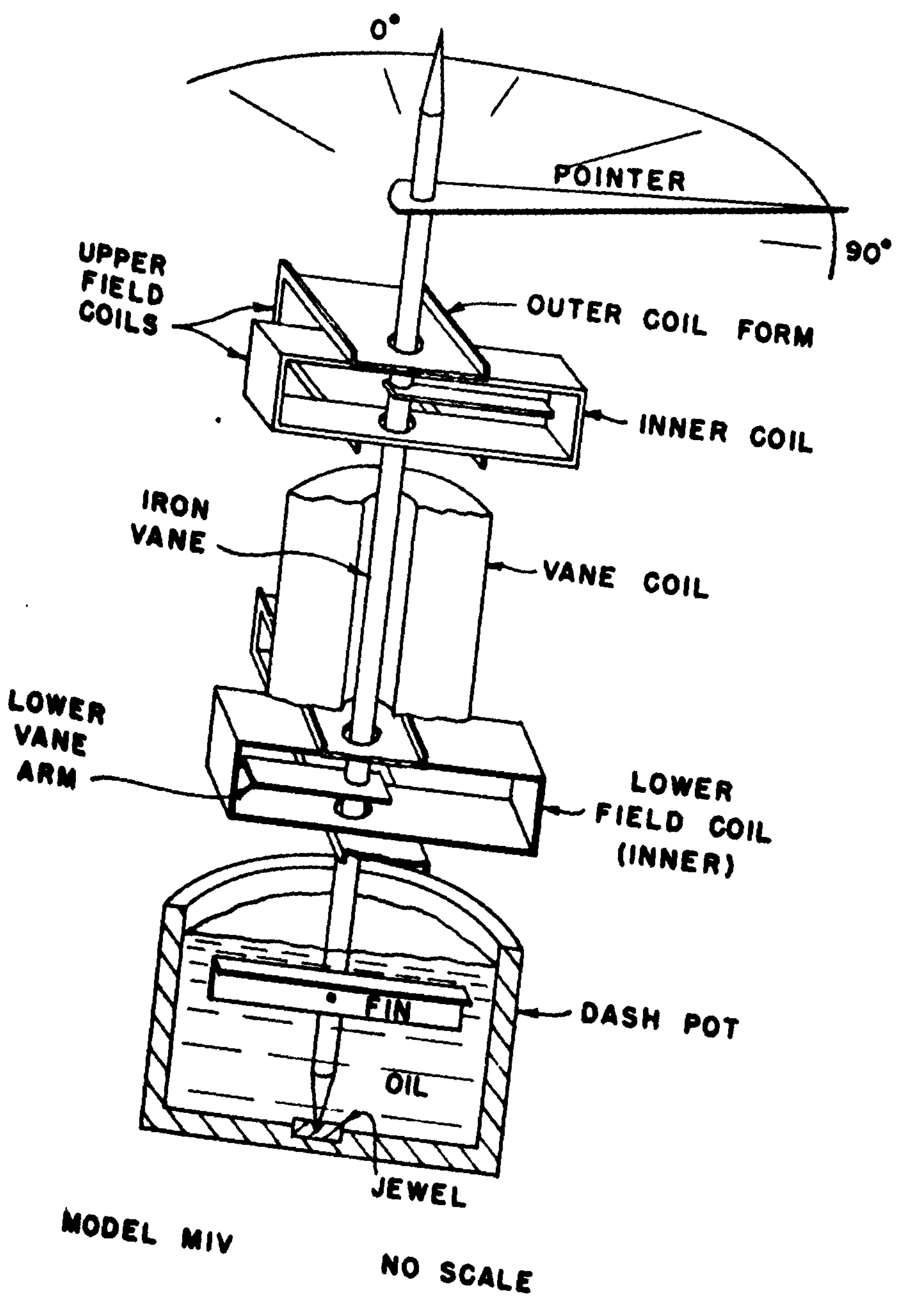

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